

AFRL-VA-WP-TP-2003-340

**A SYSTEM TO PREVENT MID AIR
COLLISIONS**

**Donald E. Swihart
Edward Griffin
Bertil Brännström
Ragnar Rosengren
Paul Doane**



OCTOBER 2003

Approved for public release; distribution is unlimited.

This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

20031112 110

**AIR VEHICLES DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542**

REPORT DOCUMENTATION PAGEForm Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE (DD-MM-YY) October 2003		2. REPORT TYPE Conference Paper Preprint		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE A SYSTEM TO PREVENT MID AIR COLLISIONS				5a. CONTRACT NUMBER In-house	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER N/A	
6. AUTHOR(S) Donald E. Swihart (AFRL/VACC) Edward Griffin (Lockheed Martin Aeronautics) Bertil Brännström (Försvaret Materielverk) Ragnar Rosengren (Saab AB) Paul Doane (Boeing)				5d. PROJECT NUMBER N/A	
				5e. TASK NUMBER N/A	
				5f. WORK UNIT NUMBER N/A	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Control Systems Development and Application Branch (AFRL/VACC) Control Sciences Division Air Vehicles Directorate Air Force Research Laboratory, Air Force Materiel Command Wright-Patterson AFB, OH 45433-7542 Lockheed Martin Aeronautics, Ft. Worth, TX Försvaret Materielverk, Stockholm, Sweden Saab AB, Linköping, Sweden The Boeing Company, St. Louis, MO				8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-VA-WP-TP-2003-340	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Vehicles Directorate Air Force Research Laboratory Air Force Materiel Command Wright-Patterson Air Force Base, OH 45433-7542				10. SPONSORING/MONITORING AGENCY ACRONYM(S) AFRL/VACC	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-VA-WP-TP-2003-340	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES To be presented at the 10th Saint Petersburg International Conference, St. Petersburg, Russia, 26-28 May 2003. This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.					
14. ABSTRACT Tomorrow's Air Force will use Unmanned Air Vehicles (UAV) for a number of missions. High-risk missions in which pilot losses are unacceptable are ideal candidates for such vehicles. This paper describes the program for a safety system that prevents air-to-air collisions. It is currently in early stages of development and has application for both military and commercial.					
15. SUBJECT TERMS Data Links, Auto ACAS, Automatic control, aircraft response model					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT: SAR	18. NUMBER OF PAGES 12	19a. NAME OF RESPONSIBLE PERSON (Monitor) Donald Swihart 19b. TELEPHONE NUMBER (Include Area Code) (937) 255-8281
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

A SYSTEM TO PREVENT MID AIR COLLISIONS

Donald E. Swihart, MSEE, Program Manager
Air Force Research Laboratory, Wright-Patterson AFB, OH
Donald.swihart@wpafb.af.mil

Edward Griffin, BSCE, Program Manager
Lockheed Martin Aeronautics, Ft. Worth TX
Edward.m.griffin@lmco.com

Bertil Brännström, MSAE, Senior Advisor of Aeronautical Technologies
Försvaret Materielverk (FMV), Stockholm, Sweden
bertil.brannstrom@fmv.se

Ragnar Rosengren, MSEE & Applied Physics, Program Manager
Saab AB, Linköping, Sweden
Ragnar.rosengren@saab.se

Paul Doane, MSAE, Engineering Manager
The Boeing Company, ST. Louis, MO
Paul.m.doane@boeing.com

Abstract

Tomorrow's Air Force will use Unmanned Air Vehicles (UAV) for a number of missions. High-risk missions in which pilot losses are unacceptable are ideal candidates for such vehicles. Swarming large numbers of vehicles to saturate enemy defenses and bring overwhelming force to a conflict for extended periods of time is another possibility. Whatever missions are chosen for these vehicles, their numbers and use will significantly increase in the future. We must find ways to allow safe operation with manned aircraft and UAVs in the same airspace. Although collision is to be prevented, close flight with other aircraft is necessary for formation, refueling, and combat training.

Currently, multiple UAV flights are not performed due to the difficulty in the control algorithms and the lack of redundancy to handle failures. Control algorithm designs can be achieved to provide for multiple UAV operations but single thread system failures remains a problem. Also, unforeseen circumstances such as ground controllers flying the wrong course can cause air vehicles to arrive in the same airspace at the same time, which can cause a collision. Even in the case of autonomous UAV operation, flight management errors could result in time of arrival errors and air vehicle collisions. As more of these systems are utilized, the methods to control them become even more difficult and the possibility of something going wrong increases. There is also a desire to enable UAV flights within commercial airspace. This desire cannot be achieved until a proven method to prevent air-to-air collisions is implemented.

The design of an Automatic Air Collision Avoidance System (ACAS) is intended to prevent air-to-air collisions between air vehicles. The Auto ACAS is not intended to replace existing designs such as the Traffic Alert and Collision Avoidance System (TCAS) but is intended to accomplish a recovery at the last instant to prevent a collision. TCAS and other systems in use today provide situational awareness and traffic advisories to enable pilots to perform de-confliction and manual avoidance maneuver and remain several miles apart. In contrast, Auto ACAS assumes such de-confliction and manual avoidance attempts have not succeeded and operates in a time span that does not allow for manual pilot reactions, thus it must be highly integrated and automated in operation. An automated TCAS could be used to keep apart UAVs and commercial airliners but

this kind of design may be difficult to implement due to the fact that it was initially designed to instruct the pilot to make course changes and not automatically take control of the aircraft.

Automatic collision avoidance is necessary if Unmanned Aerial Vehicles (UAVs) are to fly in the same air space, in formation, accompany manned fighters on combat missions, and transition civil airspace. These vehicles will, in some manner, have to "see and avoid" other aircraft. An automated air collision avoidance system will fulfill a part of this need. It will automatically maneuver an aircraft, at the last instant, to avoid an air-to-air collision. It will function in a manner similar to a pilot avoiding a collision. It is a system that must be reliable, verifiable, and partially redundant, forming the last line of defense against collisions. It must provide nuisance free operation and allow safe interoperability. Of particular interest are criteria to enable a safe, nuisance free system that will have embedded rules of the road for all encounters. Autonomous control of unmanned aerial vehicles is a goal for the US Air Force in the future. However, flying multiple unmanned vehicles in the same tactical airspace with manned fighters presents very challenging problems. Automatic collision avoidance is a necessary step in moving toward this goal.

This paper will discuss the integration of a data link in the design of an Auto ACAS for aircraft, which is intended to prevent air-to-air collisions between air vehicles

Introduction

The Air Force Research Laboratory developed an Automatic Ground Collision Avoidance System (GCAS) several years ago. The GCAS was based on a Digital Terrain System (DTS), which produced a digital map of the terrain surrounding the aircraft. The aircraft was placed on the map utilizing a radar altimeter and remained on the map using the aircraft Inertial Navigation System (INS). An accurate Aircraft Response Model (ARM) was developed and utilized to produce the future trajectory of the aircraft. A Minimum Descent Altitude (MDA) was placed over the digital terrain. The MDA was selectable by the pilot and was used as a buffer. If the future trajectory intersected the MDA, an advisory in the form of chevrons was displayed on the Heads Up Display (HUD). If the pilot did not correct the aircraft trajectory, the chevrons would move together until a break X was produced. At the point of the break X, an automatic roll to wings level 5G flyup would occur. Voice warnings at flyup and termination were "flyup - flyup" and "You've got it". The design was accomplished in the 1991 - 92-time period and was utilized specifically for low-level night attack flight tests. The initial auto GCAS was developed on an F-16 and was designed to only utilize a portion of the F-16 flight envelope.

In 1996, the Swedish Air Force joined AFRL in a cooperative effort to expand the limited envelope of the Auto GCAS. The program began in early 1997 and ended in late 1998 with a very successful flight test. In the early

stage of the program, a nuisance criteria was developed to ensure that activation of the auto flyup would only occur when required and never interfere with the pilot.

The idea of developing an automatic air collision avoidance system (ACAS) originated when the Air Force asked how to:

a) Fly multiple UAVs autonomously in the same airspace.

b) Fly multiple UAVs with manned aircraft

One method would be to have each UAV controlled by an operator and fly them like manned aircraft. This method becomes quite challenging when the number of UAVs gets large, failures occur, or when operator errors occur.

Another method would be to use the existing Traffic Collision Alert System (TCAS) and automate it. The TCAS was developed for commercial airlines and operates by warning the pilot when two airliners become too close. The pilot must take appropriate action, which is in the form of a climb or dive. To automate TCAS, it must be connected to the flight control system so that the warning would be turned into an action and a maneuver. At first glance this would seem to be the answer but there are problems with this design. First, TCAS operates at very large distances (20-40 miles) thus would not allow close formation flying. Secondly, TCAS was developed to be a manual system. This fact at first must seem trivial to the reader but the automation of a system that interferes with normal operation of a flight control computer must be designed carefully. The software must go through a more extensive test for a flight

control system than for other avionics systems. In most instances hardware and software redundancy is required to obtain the safety requirements demanded by a flight control system. There are methods to allow single thread or non redundant systems to be connected to a flight control system but these methods are not normally applied to manually operated systems.

About the same time as questions were being raised on UAVs, the Air Force Safety Center asked if AFRL could design a system similar to Auto GCAS for preventing air-to-air mishaps in military aircraft, specifically fighters.

The approach to obtain an Auto ACAS was to utilize lessons learned from the Auto GCAS and apply them to the new Auto ACAS design. It was assumed from the beginning that an Auto ACAS would be much more complex than an Auto GCAS for several reasons. First, the ground was large and easily identifiable for Auto GCAS operation. Second, we had several years experience in developing different methods to achieve the Auto GCAS design. Lastly, the ground was a stationary target and always in the same place.

These three facts were not the case for an air-to-air engagement. Therefore, a decision was made to accomplish a concept study to determine if an Auto ACAS was feasible and if so what kind of algorithm would be required to achieve a robust design. The U.S. and the Kingdom of Sweden had entered into a Project Agreement (PA) under a Technology Research and Development Program (TRDP) for the Auto GCAS program several years ago. Sweden had been interested in preventing air-to-air mishaps also, so they again approved of a second PA under the TRDP for the Auto ACAS program. The Boeing Company, Lockheed Martin Aeronautics, and Saab AB were contracted to conduct the concept study from May 2000 to March 2001. The concept study results will be discussed later, but in general it was considered feasible to design an Auto ACAS.

The purposes of the study were to determine the algorithm requirements (feasibility, design approach, iteration frequency, data link update rates, etc), the available technologies (sensors, data links, etc) to replicate the "situation awareness"

provided by a pilot's vision, and to lay out and cost a feasible program path.

Program Path

The management of the program was dictated by the PA and consisted of the Air Vehicles Directorate, Air Force Research Laboratory, Wright Patterson Air Force Base and Sweden's Försvaret Materielverk (FMV).

The plan was to design, develop, integrate, and flight test an algorithm that would prevent midair collisions. A team was assembled consisting of government engineers and test pilots from Wright-Patterson AFB, Edwards AFB, Eglin AFB, NASA Dryden, and FMV.

Contracted portions of the effort were performed by Lockheed Martin Aeronautics, Fort Worth, Texas; The Boeing Company, St. Louis, Mo.; Saab AB, Linköping, Sweden; Bihle Applied Research, Hampton VA, and Veridian Engineering, Buffalo, N.Y., and Dayton Ohio.

All three contractors were capable of designing an algorithm, integrating it into an air vehicle, and flight testing it. The program path required that the use of the most economical approach to complete the program should be implemented.

The test aircraft was a major deciding process in choosing the contractor that would accomplish the integration. During the concept study, several requirements were derived on the type of test aircraft. Initially, Sweden was interested in providing an aircraft but later decided that it would be too complicated to obtain. The F-16 had been used for the Auto GCAS program and after several meetings, it was decided that the F-16 would also be used for the Auto ACAS flight test. Therefore, since Lockheed built the F-16, they were chosen as the integrator for the Auto ACAS.

It was decided to have Boeing and Saab design and simulate the algorithm. Requirements for the algorithm were provided to the two contractors.

The algorithm required proper data for it to initiate an escape maneuver. There were basically two methods to accomplish receiving the required data. One was to use a data link that each aircraft would have on board and the other would be to utilize some kind of sensor to provide the necessary

data. During the concept study, it was determined that a data link would be the most economical approach for the Auto ACAS program. The data link approach could also allow each aircraft to receive the required flight parameters from the other aircraft resulting in the capability for both aircraft to maneuver.

Proposals and resulting schedules were obtained from the contractors and the Auto ACAS program was formulated.

Program Operation

Communication between all parties was a ground rule for the operation of the program. Technical Interchange Meetings (TIM) were established and scheduled to be held every two months. The host for the TIMs was rotated between all team members. In addition to the TIMs, telecons were held three times a week to discuss algorithm design issues. There were also management telecons held during the month where no TIM was held. During the flight test planning stage of the program, two telecons per week were held. This kind of communication provided great working relationships between all team members and was a driving force to allow the program managers to control both funding and schedule.

A preliminary version of the algorithm was given to Lockheed early in the program to allow them to set up the integration process. Lockheed was able to design the interface software, which allowed the algorithm designers to make changes to the algorithm and not interfere with the aircraft integration process. This was an important management decision that provided schedule risk reduction.

Discussion of Requirements

Due to the fact that the algorithm must operate on a piloted vehicle, the system could not interfere with normal vehicle operation. Since the operation of Auto ACAS required that the algorithm take control of the aircraft, it needed to function only after the pilot would have maneuvered the aircraft. If the algorithm activated too early, it could be perceived as a nuisance to the pilot. Therefore, one requirement would

be that it not cause a nuisance to the pilot. Along the same lines of thought, the system should provide a maneuver that would function similar to what a pilot would perform. The automatic maneuver also required some sort of termination criteria. The system should activate when necessary to prevent a collision and terminate when the threat of collision has past.

Safety

Flight control systems are designed with redundancy to achieve the required loss of control parameter. Systems are usually triplex or quad redundant in order to achieve this parameter. In a quad system, a first failure is voted off and the system continues to operate as a triplex system. A second like failure will again be voted off and the system continues to operate as a dual system. These systems are called two fail operate.

If a single thread avionics subsystem is integrated into the flight control system, one method of failure detection is to create a similar function utilizing redundant subsystems. An example that has been employed is to utilize the quad flight control gyros to give a short time calculation for an Inertial Navigation System (INS). The INS is utilized in many automatic maneuvers to provide information that holds the aircraft in a certain position during an automatic maneuver. Example: Suppose the INS has a hard over failure. Each of the quad digital flight control system computers monitors the INS and when the failure is detected, the flight control gyros can provide data for the flight control computer to compute the INS function for a short time period. The time required is normally very short due to the short duration of the automatic maneuver.

There are other types of methods to ensure safe avionics integration such as sending a calculation for an avionics computer to accomplish. Designing a coded message that the avionics computer sends at a specific periodic rate is also a method employed.

Algorithm Operation

The Auto ACAS algorithm was designed to claim space along a predicted escape

trajectory, which the aircraft uses whenever an avoidance maneuver is required. The major benefit of using an escape trajectory was that it could be predicted much more accurately than the probable trajectory, which the aircraft could follow if no avoidance was executed. This is because the escape trajectory was executed automatically in a predetermined way by the Auto ACAS algorithm, whereas the probable trajectory was affected by the change in pilot commands. The size of the claimed space was computed using knowledge of the wingspan, navigation uncertainty and accuracy of the predicted trajectory compared to the one the automatic digital flight control system (DFLCS) commands the aircraft to follow.

Each aircraft sends its predicted escape maneuver and the size of the claimed space along this track to the other aircraft, using the data link. Fig. 1 shows the escape trajectories and the uncertainties (depicted by the cones) caused by the latencies in the system.

The escape maneuver directions were chosen to maximize the minimum distance between all aircraft. In this way the avoidance will be executed at the last possible instant and the system will thus guarantee a very low nuisance level.

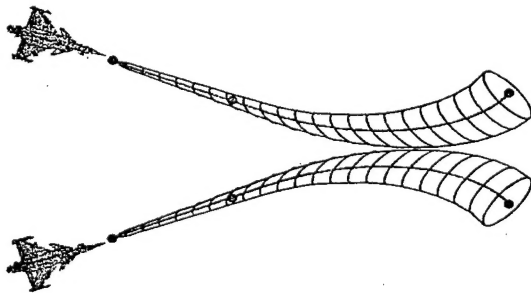


Fig. 1. Collision detection using predicted escape maneuvers

Escape Maneuvers

The Auto ACAS algorithm will choose between two different escape maneuvers, one in pitch and the other in roll. For piloted fighters, the pitch maneuver will be a 5G pull. For the UAV, the pitch maneuver will be maximum G available. The other escape maneuver is either a roll right or roll left, followed by a pull to the Gs explained

above. The roll rate was 60 degrees per second for piloted fighter aircraft, and a roll at the maximum roll rate for the UAV. Calculating the amount of angle needed to roll the wings parallel to the collision plane generates the roll command.

As discussed above, the algorithm was designed to initiate the selected escape maneuver at the last instant before the collision becomes inevitable, and to terminate the escape maneuver as soon as the separation distance begins to increase.

Sensor Operation

As discussed earlier, the choice of a data link for the Auto ACAS flight test was one of availability and cost, not performance. For data link operation, each air vehicle must have the capability to link flight parameters to each of the other air vehicles. This in-network process can function quite well in relatively small groups of vehicles but if the need arises to provide collision prevention between large groups or swarms of air vehicles, the system breaks down.

Sensors do not need exact compatibility between air vehicles. These devices can provide the required parameters for the algorithm to function properly. They do not depend on information exchange that is required by data link operation. The host vehicle can maneuver within any number of other platforms without colliding. Each host vehicle does not need to have identical sensors on board to accomplish the collision prevention function. Sensors can provide protection from out-of-network aircraft, which are aircraft that have no data link or sensor on board.

Flight Test Plan

To implement the Auto ACAS algorithm into an aircraft, certain subsystems must be available. One is that the aircraft requires a Digital Flight Control System (DFLCS) and fly-by-wire design is also recommended. The DFLCS provides the capability to monitor other subsystems within the avionics for failure detection and resolution. As discussed earlier, the choice platform for the flight test of the Auto ACAS algorithm was the F-16. The flight test plan required the use of two aircraft to show that the

algorithm would maneuver both aircraft away from each other.

One of the test aircraft chosen was the Variable Stability In Flight Simulator Test Aircraft or VISTA/F-16. The reason for VISTA was to be able to simulate a UAV. The Auto ACAS algorithm will be integrated into the Variable Stability System (VSS) computer on VISTA. The VSS is a computer that provides the simulation capability for VISTA. For the Auto ACAS program, VISTA would have two purposes, to simulate an F-16 and to simulate a UAV. The second aircraft for the flight test is an F-16.

The integration process for the F-16 is much more involved than on VISTA. This is because the F-16 will utilize flight quality hardware to host the Auto ACAS algorithm. The software must be simulated within the hardware and validated/verified to ensure that it is safe to flight test. The software on VISTA is hosted on the VSS, which is monitored during flight by the digital flight control computer. Therefore, the software testing is limited to the VSS and does not impact normal F-16 hardware.

The flight test is set up to first fly VISTA with a virtual target provided by the data link. These flights are intended to show how the algorithm performs in flight. It will also provide information on data link operation during flight. After the VISTA flights, the algorithm will be integrated into and flight tested on an F-16. The first flights on the F-16 will also be with a virtual target to ensure proper operation of the algorithm. The flight test will then progress to both VISTA and the F-16 to show that the Auto ACAS algorithm can provide collision prevention between two aircraft. The algorithm will be set to activate at large distances at first with both altitude and longitude offsets for safety purposes.

Conclusions

The Auto ACAS program formulation described in this paper has operated quite well thus far. The program is on schedule and within budget. Excellent teamwork between all parties has been achieved.

The Auto ACAS algorithm will be flight tested to show that it can safely maneuver a manned air vehicle automatically and not

interfere with normal pilot operations. It will only be required to function for very short time periods and only to prevent a potentially fatal mishap. The algorithm will also show that it can safely maneuver a VISTA simulated UAV.

As a result, the Auto ACAS can provide the capability for UAVs to fly close together without collisions. This will be the first necessary step in providing the capability to allow swarming of UAVs. The approach described can be used to develop a system for both manned fighters and UAVs.

The system at the current stage of development indicates that it can provide the computational capabilities needed for a nuisance free design. Simulation results thus far have shown that the Auto ACAS has achieved nuisance free operation.

The Auto ACAS program has shown that great teamwork is beneficial in creating a successful effort.